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RARE-EARTH MINERALS AND METALS

By James B. Hedrick and David A. Templeton

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RARE-EARTH MINERALS AND METALS

U.S.
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Manuel Lujan, Jr.
Secretary

BUREAU
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MINES

T S Ary
Director

May 1991

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COVER PHOTO
The F-15 Aircraft displays the fuselage-mounted AIM-9 "Sparrow" missile and wing-mounted AIM-7 "Sidewinder" missile. Both missiles contain high-strength samarium-cobalt permanent magnet motors to control the moving flight control surfaces (fins). (Photo courtesy of the U.S. Department of Defense.)

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RARE-EARTH MINERALS AND METALS

By James B. Hedrick and David A. Templeton

Messrs. Hedrick and Templeton are physical scientists with the Branch of Nonferrous Metals. Mr. Hedrick has covered rare earths for 9 years. Mr. Templeton has shared coverage of the commodity for 2 years. Domestic survey data were prepared by Ms. Imogene P. Bynum, Nonferrous Metals Data Section. International data were prepared by Mr. Harold Willis, International Data Section.

Domestic consumption of the rare earths was almost double the quantity used in 1988, mine production increased sharply, and the industry performed well amid increased international competition. Traditional markets of the rare earths, such as petroleum catalysts and metallurgical additives, continued a downward trend while new and emerging markets, such as neodymium-iron-boron permanent magnets, advanced ceramics, and automotive catalysts, showed strong growth. The television and lamp phosphors market was unchanged, and glass polishing applications increased markedly. Demand for rare earths consumed in high-temperature superconductors was small; however, technologic breakthroughs in 1989 increased the prospects for commercial development of rare-earth superconductors.

TABLE 1

SALIENT U.S. RARE-EARTH STATISTICS

(Metric tons of rare-earth oxides (REO) unless otherwise specified)

	1985	1986	1987	1988	1989
Production of rare-earth concentrates[1]	13,428	11,094	16,710	11,533	20,787
Exports:[e 2]					
Cerium compounds	NA	NA	NA	NA	1,433
Rare-earth metals, scandium, and yttrium	NA	NA	NA	NA	510
Ore and concentrate	4,419	r3,911	r3,041	r4,415	NA
Ferrocerium and pyrophoric alloys	23	29	r72	r32	e31
Imports for consumption:[e 2]					
Monazite	3,132	1,628	617	1,058	426
Metals, alloys, oxides, compounds	1,124	r751	r724	r912	6,125
Stocks, producers and processors, yearend	W	W	W	W	W
Consumption, apparent[e]	12,100	r10,900	r11,100	r16,800	27,770
Prices, yearend, dollars per kilogram:					
Bastnasite concentrate, REO basis	2.14	2.14	2.31	2.43	2.65
Monazite concentrate, REO basis	1.09	1.06	.90	1.15	1.19
Mischmetal, metal basis	12.35	12.35	12.35	12.35	12.35
Employment, mine and mill[e 3]	330	283	r301	320	381
Net import reliance[e 4] as a percent of apparent consumption	(5)	(6)	(6)	r29.00	23.49

[e]Estimated. [r]Revised. NA Not available. W Withheld to avoid disclosing company proprietary data.

[1]Comprises only the rare earths derived from bastnasite, as reported in Unocal Corp. annual reports.

[2]Because of the implementation of the Harmonized Tariff System in Jan. 1989, import and export categories for 1989 are not necessarily comparable with those of previous years.

[3]Employment at a rare-earth mine in California and at a mineral sands operation in Florida. The latter mine produced monazite concentrate as a byproduct of mining ilmenite, rutile, and zircon, and employees were not assigned to specific commodities.

[4]Imports minus exports plus adjustments for Government and industry stock changes.

[5]Increase in industry stocks exceeded net imports.

[6]Net exporter.

PRODUCTION

Bastnasite, a rare-earth fluocarbonate mineral, was mined by Molycorp, Inc. at its Mountain Pass, CA, open pit mine. Although mine output increased, Molycorp's sales of rare earths reportedly decreased slightly, mainly as a result of weak foreign demand and increased international competition. Molycorp completed an expansion of its separation facilities to produce additional quantities of dysprosium and neodymium oxides for the permanent magnet industry. The company also began production of erbium, an element used in glass coloration (pink), lasers that emit light in the blue wavelengths, and as a burnable poison in nuclear reactors. Monazite, a rare-earth phosphate mineral, was produced as a byproduct of titanium and zirconium minerals production by Associated Minerals (USA) Inc., a subsidiary of the Australian company Renison Goldfields Consolidated Ltd. (RGC). Associated Minerals operated its placer dredging operation at Green Cove Springs, FL. The addition of a spud barge to the Florida operation has reportedly increased ore mining capability significantly and offset falling heavy-mineral sand grades. The barge addition allowed the floating concentrator to operate at design capacity. Monazite from all of RGC's mineral sands operations, including Green Cove Springs, was fully sold under long-term contracts.[1]

Imperial Mining Co. produced minor amounts of a mixed monazite-xenotime-zircon concentrate at a gold and industrial sand and gravel mine in North Carolina. To improve byproduct heavy-mineral sands recovery and delineate ore, Imperial was seeking a joint-venture partner to provide capital and expertise.

Scandium concentrate, produced in prior years in Utah, was processed by Sausville Chemical Co., Garfield, NJ, and Boulder Scientific Co., Mead, CO, into high-purity scandium oxide. Facilities to purify scandium compounds were operated by Research Chemicals Div. of Rhône-Poulenc Inc., Phoenix, AZ, and the Materials Preparation Center, Ames, IA.

Principal domestic producers of neodymium-iron-boron magnet alloys were Molycorp, Neomet Corp., and Research Chemicals. Leading U.S. producers of rare-earth magnets were the Delco Remy Div. of General Motors Corp., Hitachi Magnetics, Crucible Magnetic Materials, and IG Technologies.

In New Mexico, Molycorp and the Mescalero Apache Tribe announced a joint-venture agreement to develop a zirconium and yttrium-bearing deposit on the tribe's reservation. The deposit, identified by Molycorp in 1985, contains eudialyte, an yttrium-bearing zirconium silicate mineral. Reported reserves were 2.4 million tons grading 1.2% zirconium oxide and 0.18% yttrium oxide. Initial metallurgical tests by Molycorp indicate that the ore could be economically processed with conventional heap-leach technology.

In the southeastern United States, Associated Minerals and its parent company, RGC, announced completion of the exploration phase of the Old Hickory heavy-mineral sands deposit located southwest of Richmond, VA. The deposit reportedly contains 7.3 million metric tons of heavy minerals with minor amounts of monazite. Mining of the Old Hickory deposit could begin in 3 to 5 years.

CONSUMPTION AND USES

Domestic rare-earth processors consumed 72% more rare earths in 1989 than they consumed in 1988. Bastnasite consumption was 73% higher than in 1988, but monazite consumption was 42% lower. Shipments of rare-earth products from domestic processors of ore, concentrates, and intermediate concentrates was equivalent to 12,975 tons of rare earth oxide (REO), up 31% from the 9,867 tons shipped in 1988.

Consumption of mixed rare-earth compounds decreased 49% from the 1988 level, while consumption of purified compounds increased 98%. Higher consumption of purified compounds was the result of continued strong demand for neodymium, dysprosium, and certain other rare earths used in high-strength permanent magnets, cerium used in automotive catalytic converter materials and glass, and for yttrium used in a variety of ceramic and refractory applications.

The producers of mischmetal, rare-earth silicide, and other rare-earth alloys consumed 30% more rare earths in 1989 than in 1988, while shipments of these goods fell 2% during the same period. Shipments of high-purity rare-earth metals increased 22% during the year.

The approximate distribution of rare earths by use, based on information supplied by primary processors and some consumers, was as follows: catalysts in petroleum, chemical, and pollution control applications, 42%; metallurgical uses as iron and steel additives, alloys, and mischmetal, 14%; ceramics and in glass polishing compounds and as glass additives, 43%; and miscellaneous uses in phosphors, electronics, permanent magnets, and in lighting and research applications, 1%.

The glass industry's principal use of rare earths, mainly cerium concentrate or cerium oxide, was as polishing compounds for lenses, mirrors, cut crystal, television and other cathode-ray tube (CRT) faceplates, gem stones, and plate glass. Rare-earth compounds were also used as additives to glass used in automobiles, food and beverage containers, television and CRT faceplates, radiation shielding windows, opthalmic lenses, lasers, incandescent and fluorescent lights, and optical, photochromic, filter, and photographic lenses. The rare-earth additives acted as colorants, color correctors, and decolorizers, as stabilizers against discoloration from ultraviolet light and against browning caused by high-energy radiation, as dopants in laser glass, as modifiers to increase the refractive indices and decrease dispersion, and as absorbers of ultraviolet and visible light.

Phosphors containing rare earths were used in color television tubes, radar screens, avionic and data displays, X-ray intensifying screens, low- and high-pressure mercury vapor lights, electronic thermometers, and trichromatic fluorescent lamps.

The ceramics industry used purified rare earths in pigments, heating elements, dielectric and conductive ceramics, thermal and/or flash protective devices, stereoviewing systems, data printers, image storage devices, and as principal constituents and stabilizers in high-temperature refractories, such as yttria-stabilized zirconia, and in glasses and paints.

Rare-earth compounds had applications in petroleum fluid cracking catalysts, noncracking catalysts, oxygen-sensing electrolytes, computer bubble domain memories, dyes and softeners for textiles, electronic components, nuclear fuel reprocessing, microwave applications, incandescent gas mantles, laser crystals, fiber optics, carbon arc lighting, synthetic gem stones, and superconductors.

Rare-earth permanent magnets were used in electric motors; alternators; generators; line printers; computer disk-drive actuators; proton linear accelerators; synchronous torque couples; eddy current brakes; microwave transmission focusing; magnetrons; klystrons; medical and dental applications, including nuclear magnetic resonance imaging; traveling wave tubes, metallic separators; aerospace applications, including electric actuators for ailerons and rudders; and in speakers, headphones, microphones, and tape drives.

Metallurgical applications of rare earths included alloys and additives in high-strength, low-alloy steels, gray and ductile iron, stainless and carbon steels, high-temperature and corrosion-resistant metals, hydrogen storage alloys used in heat exchangers and fuel cells, lighter flints, armaments, permanent magnets, neutron converter foils, special lead fuses, target materials for sealed-tube neutron generators, and high-voltage transmission cable.

STOCKS

Stocks of rare-earth ores and concentrates held by 19 producing, processing, and consuming companies decreased 54%. Bastnasite concentrate stocks held by the principal producer and six other processors decreased 59% from the 1988 level. Yearend stocks of monazite increased 35%, while stocks of yttrium concentrate decreased 10%.

Stocks of other rare-earth concentrates fell 43%. Stocks of mixed rare-earths compounds increased 12%, as stocks of purified compounds decreased 55%. Yearend stocks of mischmetal, rare-earth silicide, and other alloys containing rare earths gained 37%, as inventories of high-purity rare-earth metals were off 78%.

PRICES

Published prices for the rare earths were generally nominal and subject to change without notice. Increased foreign competition resulted in competitive pricing policies in the United States in 1989 with prices for most rare-earth products quoted on a daily basis.

Prices quoted by Molycorp for unleached, leached, and calcined bastnasite in standard quantities, containing 60%, 70%, and 85% REO, were $1.15, $1.20, and $1.40 per pound of contained REO, respectively, at yearend 1989. These prices were respectively $0.10 per pound more than at yearend 1988.

The price range of Australian monazite (minimum 55% rare-earth oxide, including thoria, f.o.b./f.i.d.),[2] as quoted in Australian dollars (A$),[3] increased from A$700-A$780 per ton at yearend 1988, to A$780-A$880 per ton by yearend 1989. The U.S. price range, converted from Australian dollars, increased from US$598-US$666[4] in 1988 to US$616-US$695[5] in 1989. The average declared value of imported monazite increased in 1989 to $685 per ton, up $85 from the 1988 value.

The yearend price quoted in Industrial Minerals (London) for yttrium concentrate (60% Y_2O_3, f.o.b. Malaysia) was $32-$33 per kilogram.

The price of cerium concentrate quoted by American Metal Market was $1.55 per pound of contained cerium oxide at yearend 1989, an increase of $0.15 from the previous year. The yearend price of lanthanum concentrate remained unchanged from the 1988 level at $1.40 per pound of REO contained.

Mischmetal (99.8%, lots over 100 pounds, f.o.b. shipping point) prices for 1989, quoted by Reactive Metals and Alloys Co., were $5.00 per pound.

The price for neodymium-iron-boron alloy, compiled by the Bureau of Mines, averaged $15 per pound, f.o.b. shipping point, 1,000 pound minimum.

Molycorp quoted prices for lanthanide (rare earth) and yttrium oxides, net 30 days, f.o.b. Louviers, CO, Mountain Pass, CA, or York, PA, effective October 1, 1988, and throughout 1989, as follows:

Product (oxide)	Percent[1] purity	Quantity (pounds)	Price per pound
Cerium	99.0	200.0	$8.75
Europium	99.99	25.0	745.00
Gadolinium	99.99	55.0	65.00
Lanthanum	99.99	300.0	8.75
Neodymium	96.0	300.0	6.75
Do.	99.9	50.0	40.00
Praseodymium	96.0	300.0	16.80
Samarium	96.0	55.0	65.00
Terbium	99.9	44.1	375.00
Yttrium	99.99	50.0	52.50

[1]Purity expressed as percent of total REO.

Molycorp also quoted prices for lanthanide (rare earth) compounds, net 30 days, f.o.b. York, PA, or Louviers, CO, effective November 15, 1989, as follows:

Product (compound)	Percent[1] purity	Quantity (pounds)	Price[2] per pound
Cerium carbonate	99.0	150	$5.10
Cerium fluoride	Tech grade	250	3.00
Cerium nitrate	96.0	250	2.35
Lanthanide chloride	46.0	525	1.00
Lanthanum carbonate	99.9	175	5.90
Lanthanum-lanthanide chloride	46.0	525	.95
Lanthanum-lanthanide carbonate	60.0	200	2.45
Lanthanum-lanthanide nitrate	39.0	250	1.75
Neodymium carbonate	96.0	300	4.50

[1]Purity expressed in terms of REO equivalent.
[2]Priced on a contained REO basis.

Rhône-Poulenc quoted rare-earth prices, per kilogram, net 30 days, f.o.b. New Brunswick, NJ, or duty paid at point of entry, as follows:

Product (oxide)	Percent purity	Quantity (kilograms)	Price per kilogram
Cerium	99.5	20	$25.75
Dysprosium	95.0	20	132.00
Erbium	96.0	20	190.00
Europium	99.99	10	1,960.00
Gadolinium	99.99	50	136.50
Holmium	99.9	5	510.00
Lanthanum	99.99	25	23.00
Lutetium	99.99	2	7,000.00
Neodymium	95.0	20	20.00
Praseodymium	96.0	20	38.85
Samarium	96.0	25	175.00
Terbium	99.9	5	880.00
Thulium	99.9	5	3,600.00
Ytterbium	99.0	10	230.00
Yttrium	99.99	50	115.50

Nominal prices for various rare-earth oxides and metals were quoted by Research Chemicals, per kilogram, net 30 days, f.o.b. Phoenix, AZ, for yearend 1989 as follows:

Element	Oxide[1] price per kilogram
Cerium	$80.00
Dysprosium	230.00
Erbium	570.00
Europium	1,900.00
Gadolinium	180.00
Holmium	610.00
Lanthanum	55.00
Lutetium	9,000.00
Neodymium	130.00
Praseodymium	160.00
Samarium	380.00
Terbium	2,250.00
Thulium	7,200.00
Ytterbium	675.00
Yttrium	115.50

[1]Minimum 99.9%-pure, 1- to 20-kilogram quantities.

No published prices for scandium oxide were available. Yearend nominal prices for scandium oxide per kilogram, compiled by the Bureau of Mines from information from several suppliers, were as follows: 99% purity, $5,000; 99.9% purity, $9,000; 99.99% purity, $9,500; 99.999% purity, $10,000. Scandium metal prices, as listed by the Johnson Matthey Aesar Group, were as follows: 99.99% purity, lump, sublimed dendritic, $248.20 per gram; 99.9% purity, 250 micron powder, $444.00 per 2 grams; and 99.9% purity, lump, vacuum remelted, $322.00 per 2 grams.

FOREIGN TRADE

Rare-earth imports increased dramatically in 1989 from the previous year. Brazil, China, France, and India dominated the import market as shown in figure 1. Japan and Korea were the principal destinations of U.S. exports as shown in figure 2.

WORLD REVIEW

Bastnasite was the world's principal source of rare earths. It was mined as a primary product in the United States and as a byproduct of iron ore mining in China. Monazite was the second leading source of rare earths and was produced largely as a byproduct of processing minerals sands for titanium and zirconium minerals or tin minerals. The leading monazite producers were Australia, Brazil, China, India, Malaysia, the Republic of South Africa, Taiwan, and the United States. Xenotime

TABLE 2

U.S. IMPORTS FOR CONSUMPTION OF MONAZITE, BY COUNTRY

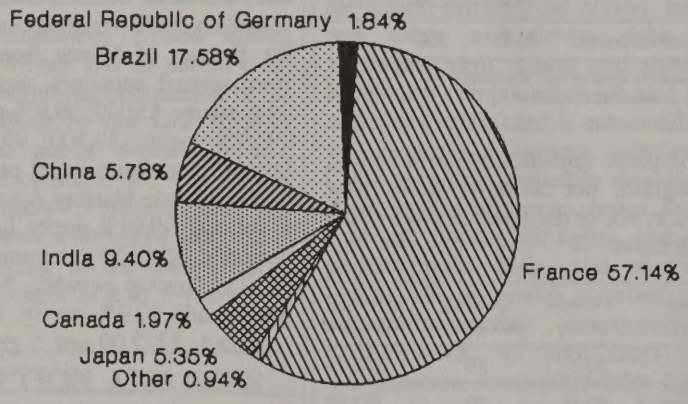
Country	1985		1986		1987		1988		1989	
	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)
Australia	5,694	$1,984	2,660	$978	—	—	382	$237	180	$117
India	—	—	300	128	—	—	—	—	—	—
Indonesia	—	—	—	—	—	—	1,144	687	794	557
Malaysia	—	—	—	—	527	$298	197	125	—	—
Thailand	—	—	—	—	594	329	201	105	—	—
Total	5,694	1,984	2,960	1,106	1,121	627	1,924	1,154	974	674
REO content[e]	3,132	XX	1,628	XX	617	XX	1,058	XX	536	XX

[e]Estimated. XX Not applicable.

Source: Bureau of the Census. REO content estimated by the Bureau of Mines.

FIGURE 1

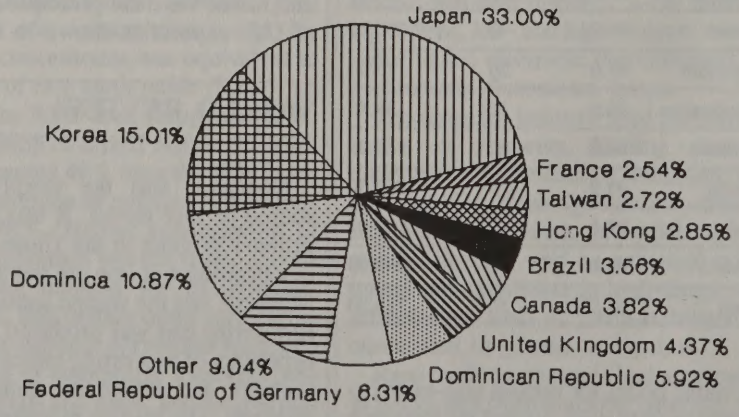
U.S. IMPORTS OF RARE EARTHS



Source: Bureau of the Census.

FIGURE 2

U.S. EXPORTS OF RARE EARTHS



Source: Bureau of the Census.

was the major source for yttrium and a minor source for the lanthanides. Xenotime was recovered primarily as a byproduct of processing for tin minerals in Indonesia, Malaysia, and Thailand, but was also produced as a byproduct of processing titanium and zirconium minerals in Australia and China. Increasing supplies of rare earths, including yttrium, were produced from rare-earth minerals in clay in China and from spent uranium leach solutions in Canada. Scandium was recovered as a byproduct of processing tungsten, tin, iron, and beryllium ores in China and was produced as a byproduct of uranium processing in the United States up to February 1989.

Capacity

Capacity to produce rare-earth minerals increased significantly in the 1980's. China and India installed the largest share of capacity during the decade.

Reserves

World reserves of rare earths were estimated by the Bureau of Mines at 45 million tons of contained REO, of which 23% is in market economy countries.[6] China had the largest share of world reserves at 76%.

Australia

Newmont Australia Ltd. and Western Rare Earths NL (previously Golden Cue NL) entered a 60-40 venture, respectively, to assess the Yangibana rare-earth deposit in Western Australia. Located about 400 kilometers northeast of Carnavon, Western Australia, the deposit reportedly contained 3.1 million tons of ore averaging 1.7% rare-earth oxide.[7]

TABLE 3

U.S. IMPORTS FOR CONSUMPTION OF RARE EARTHS, BY COUNTRY[1]

Country	1987		1988		1989	
	Quantity (kilograms)	Value	Quantity (kilograms)	Value	Quantity (kilograms)	Value
Cerium compounds:						
Austria	—	—	—	—	591	$4,606
France	80	$1,068	77,387	$38,592	221,019	964,289
Germany, Federal Republic of	370	34,223	523	42,731	3,669	154,565
Italy	—	—	—	—	173	42,413
Japan	—	—	105	1,434	25,353	770,381
Norway	—	—	—	—	1	4,000
Switzerland	2	2,863	—	—	—	—
United Kingdom	—	—	1	1,530	—	—
Total	452	38,154	78,016	84,287	250,806	1,940,254
Other mixtures of rare-earth oxides or rare-earth chlorides:						
Canada	—	—	—	—	3,628	$504,186
China	—	—	—	—	90,485	2,336,173
France	—	—	—	—	6,827,238	18,806,732
Germany, Federal Republic of	—	—	—	—	252,066	2,141,690
Hungary	—	—	—	—	2,519	9,260
Japan	—	—	—	—	132,180	1,949,341
Netherlands	—	—	—	—	4,000	4,720
Norway	—	—	—	—	11,619	1,089,092
South Africa, Republic of	—	—	—	—	106	1,067,415
Switzerland	—	—	—	—	985	19,396
U.S.S.R.	—	—	—	—	24,864	2,157,938
United Kingdom	—	—	—	—	40,905	598,972
Other	—	—	—	—	94	24,333
Total	NA	NA	NA	NA	7,390,689	30,709,248
Rare-earth oxide, excluding cerium oxide:						
Brazil	—	—	—	—	15,061	23,645
Canada	430	54,197	—	—	—	—
Chile	100	8,334	—	—	—	—
China	9,319	1,015,770	5,470	377,200	2,108	156,719
France	216,869	13,995,531	52,197	4,597,098	168,978	3,638,954
Germany, Federal Republic of	10,848	263,889	334	38,893	1,050	232,266
Hong Kong	20	29,188	—	—	200	12,084
India	—	—	—	—	290,800	460,000
Japan	5,595	611,937	2,343	318,210	11,358	1,051,525
Malaysia	5,980	119,364	—	—	—	—
Netherlands	3,815	915,912	754	135,174	—	—
Norway	3,073	426,143	1,460	152,624	1,313	125,261
South Africa, Republic of	3	38,594	—	—	—	—
Sweden	—	—	1,000	84,721	—	—
Taiwan	—	—	—	—	78	5,339
U.S.S.R.	26,516	1,663,127	7,764	484,079	4,019	381,893
United Kingdom	744	328,392	11,567	1,052,925	6,933	898,581
Total	283,312	19,470,378	82,889	7,240,924	501,898	6,986,267

See footnotes at end of table.

TABLE 3—Continued

U.S. IMPORTS FOR CONSUMPTION OF RARE EARTHS, BY COUNTRY[1]

Country	1987		1988		1989	
	Quantity (kilograms)	Value	Quantity (kilograms)	Value	Quantity (kilograms)	Value
Rare-earth metals, including scandium and yttrium:						
Austria	1,284	$35,487	—	—	4,031	$43,785
Brazil	—	—	—	—	139,896	728,099
Canada	—	—	3,147	$27,692	7,191	228,706
China	6,619	392,069	12,677	392,468	110,860	754,063
Germany, Federal Republic of	1,541	114,011	—	—	1,906	28,619
Hong Kong	5	12,738	1,000	62,018	—	—
Japan	1,724	181,385	125	18,432	7,338	259,851
Kiribati	—	—	100	4,900	—	—
Norway	—	—	—	—	222	19,450
Sweden	—	—	—	—	980	182,139
U.S.S.R.	500	32,469	403	59,765	150	23,250
United Kingdom	1,817	581,821	2,635	341,608	21,632	1,908,627
Other	—	—	—	—	30	4,232
Total	13,490	1,349,980	20,087	906,883	294,236	4,180,821
Other rare-earth metals:[2]						
Australia	—	—	752	22,282	—	—
Austria	3,733	97,314	4,108	201,193	—	—
Brazil	—	—	—	—	837,746	1,250,378
China	—	—	1,818	24,500	35,590	297,734
France	17,971	593,959	23,853	666,018	—	—
Germany, Federal Republic of	469	13,211	946	20,577	38	3,998
India	—	—	—	—	302,000	575,000
Japan	72	5,872	1,011	30,196	221,379	5,409,189
Norway	—	—	—	—	1,686	181,197
United Kingdom	([3])	1,272	—	—	3,990	364,140
Other	—	—	—	—	19	4,319
Total	22,245	711,628	32,488	964,766	1,402,448	8,085,955
Ferrocerium and other pyrophoric alloys:						
Austria	—	—	3,258	81,084	4,083	103,494
Brazil	35,890	475,256	39,075	516,944	37,031	482,609
Canada	10,142	75,057	—	—	97,490	209,155
China	—	—	—	—	1,425	1,376
Finland	—	—	—	—	1,140	3,778
France	43,701	656,671	43,714	702,545	42,541	633,583
Germany, Federal Republic of	890	24,633	—	—	5,333	42,039
Hong Kong	—	—	—	—	1,840	13,104
Italy	—	—	12,600	29,610	—	—
Japan	202	5,203	—	—	30	2,890
Korea, Republic of	—	—	—	—	18,890	109,877
Netherlands	3,280	43,434	—	—	2,100	1,785
Sweden	—	—	—	—	189	10,725
Switzerland	—	—	—	—	12,591	56,133
Taiwan	319	1,273	—	—	1,055	4,973
Thailand	257	2,329	—	—	—	—
United Kingdom	148	10,301	2,015	18,270	18,533	14,211
Total	94,829	1,294,157	100,662	1,348,453	244,271	1,689,732

NA Not available.

[1]Because of the implementation of the Harmonized Tariff System in Jan. 1989, import categories for 1989 are not necessarily comparable with those of previous years.

[2]Listed as "Other compounds of rare-earth metal, including scandium and yttrium" under the Harmonized Tariff System.

[3]Less than 1/2 unit.

Source: Bureau of the Census.

TABLE 4

U.S. EXPORTS OF RARE EARTHS, BY COUNTRY[1]

Country	1989	
	Quantity (kilograms)	Value
Thorium ore and concentrates:		
Austria	180	$117,045
France	2	29,780
Indonesia	594	413,249
Total	776	560,074
Cerium compounds:		
Argentina	1,440	12,280
Australia	34,063	292,140
Brazil	67,103	222,198
Canada	20,246	130,596
Chile	558	3,465
Colombia	2,124	15,175
France	47,754	296,549
Germany, Federal Republic of	107,816	777,276
Greece	1,926	10,120
Hong Kong	53,681	304,077
India	1,440	7,382
Ireland	1,920	8,258
Israel	2,860	14,627
Italy	10,353	62,109
Japan	599,253	2,684,774
Korea, Republic of	282,524	1,092,363
Malaysia	963	274,334
Mexico	13,563	99,636
Portugal	960	3,907
Singapore	5,047	30,923
Spain	14,609	90,884
Thailand	47,140	176,249
Taiwan	33,150	182,975
Trinadad and Tobago	8,628	105,000
United Kingdom	71,800	85,779
Uruguay	960	4,214
Other	791	38,884
Total	1,432,672	7,026,174
Rare-earth metals, including scandium and yttrium:		
Australia	2,313	22,646
Canada	43,036	356,612
China	300	95,400
Dominica	170,697	87,664
Dominican Republic	92,896	20,000
France	670	17,907
Germany, Federal Republic of	9,243	200,203
Italy	3,364	94,888
Japan	22,252	2,597,590
Korea, Republic of	213	15,686
Netherlands	268	25,580
Norway	11,442	523,043
Panama	3,938	6,902

See footnote at end of table.

Carr Boyd Minerals Ltd., owner of the Mount Weld rare-earth carbonatite deposit near Laverton, Western Australia, reportedly upgraded its measured reserves at a 20%-REO cutoff to 1.35 million tons of ore averaging 23.6% REO, including yttrium. At a 10%-REO cutoff grade, the reserves were 6.31 million tons at a grade of 16.2% REO.[8]

Rhône-Poulenc SA of France continued its quest to gain approval for a rare-earth separation plant at Pinjarra, Western Australia. Environmental concerns related to the disposal of naturally radioactive thorium have delayed the project. Rhône-Poulenc proposed a new plan to dispose of the thorium by injecting it into deep wells drilled into a saline aquifer.[9]

The Nissho Iwai Corp. of Japan purchased RZ Mines (Newcastle) Ltd. and Cable Sands Pty. Ltd. for A$240 million from Pioneer International Ltd. Nissho had been importing rutile and zircon produced by RZ Mines for 20 years before the purchase. Nissho's purchase was reportedly in response to anticipated growth in demand for zircon resulting from Japan's increase in steel production and from expanding European markets for fine ceramics. Combined, Cable and RZ Mines produced about 1,200 tons of monazite per year.[10]

Cable Sands continued development of the Jangardup heavy-mineral deposit in southwestern Western Australia. The company expected to begin mining in 1990 or 1991.[11]

An appeal to the Land and Environment Court concerning environmental issues delayed the startup of Australmin Holdings Ltd.'s mine at Newrybar, New South Wales. However, the appeal was not upheld, and the company expected production to begin in early 1990. Annual production of 30,000 tons of heavy- mineral concentrate was expected to yield 12,000 tons of rutile, 10,000 tons of zircon, and smaller quantities of monazite. Reserves at Newrybar were 22.3 million tons of ore averaging 1.1% heavy minerals.[12]

Renison Consolidated Goldfields subsidiary, Associated Minerals Consolidated, began development of the Eneabba West deposit in Western Australia. Initial mining was expected to start in 1990 or 1991. The deposit reportedly contained 230 million tons of sand with a heavy-mineral grade of 3.1%. Approximate annual production of monazite was expected to reach 2,500 tons.[13]

BHP-Utah Minerals International investigated the Beenup heavy-mineral sands

TABLE 4—Continued

U.S. EXPORTS OF RARE EARTHS, BY COUNTRY[1]

Country	1989	
	Quantity (kilograms)	Value
Poland	388	75,264
Singapore	781	53,475
Switzerland	1,163	171,519
Taiwan	20,010	49,973
United Kingdom	31,156	174,788
Venezuela	10,433	160,000
Other	274	51,483
Total	424,837	4,800,623

[1]Because of the implementation of the Harmonized Tariff System in Jan. 1989, exports are not necessarily comparable with those of previous years.

Source: Bureau of the Census.

TABLE 5

MONAZITE CONCENTRATE: WORLD PRODUCTION, BY COUNTRY[1]

(Metric tons, gross weight)

Country[2]	1985	1986	1987	1988[p]	1989[e]
Australia	18,735	14,822	12,813	11,872	13,500
Brazil	[r]3,953	[r]3,618	4,332	[r e]4,500	4,500
India[e]	4,000	4,000	4,000	4,000	4,000
Malaysia	5,808	5,959	2,908	2,920	3,100
Mozambique[e]	4	[r]3	([3])	([3])	—
South Africa, Republic of[e]	1,000	1,000	1,200	1,200	1,250
Sri Lanka[e]	200	200	200	200	200
Thailand	663	1,609	458	590	600
United States	W	W	W	W	W
Zaire	—	7	97	168	[4]175
Total	[r]34,363	[r]31,218	26,008	25,450	27,325

[e]Estimated. [p]Preliminary. [r]Revised. W Withheld to avoid disclosing company proprietary data; excluded from "Total."

[1]Table includes data available through June 27, 1990.

[2]In addition to the countries listed, China, Indonesia, North Korea, the Republic of Korea, Nigeria, and the U.S.S.R. may produce monazite, but output, if any, is not reported quantitatively, and available general information is inadequate for formulation of reliable estimates of output levels.

[3]Revised to zero.

[4]Reported figure.

deposit in the Scott River area of Western Australia. Initial studies indicated that the Beenup deposit could support dredging operations of up to 500,000 tons of heavy-mineral-bearing ore per year. Encouraging concentrations of heavy-mineral sands were reportedly found on Scott River area leases held by joint-venture partners Golden Plateau NL, Kingsgate Consolidated Ltd., and Wynarde Pty. Ltd.[14]

North Broken Hill Peko Ltd. was evaluating the feasibility of the Naracoopa mineral sands project on King Island, situated midway between Victoria and Tasmania in the Bass Strait. Reserves were estimated to contain 25 million tons of ore grading 5.2% heavy minerals.[15]

Mineral Deposits Ltd. (MDL), a subsidiary of the Australian company Broken Hill Pty. Ltd., announced the development of a mineral sands deposit near Agnes Water, Queensland. Startup of the mine was scheduled for 1991.[16]

Minproc Chemicals Pty. Ltd. and KMCC Western Australia Pty. Ltd., a subsidiary of the U.S.-based Kerr-McGee Corp., planned to start mining the Cooljarloo heavy-mineral sand deposit near Cataby, Western Australia, in the first half of 1990. Reserves of 569 million tons of ore containing 18.3 million tons of heavy minerals, including monazite, were reported.[17]

Brazil

Production of monazite concentrates in 1987 was 4,332 tons, with 177 tons from the State of Espírito Santo, a decrease from the 197 tons produced in 1986; 3,271 tons from the State of Rio de Janerio, a decrease from the 1986 production of 3,421 tons; and 884 tons from the State of Bahia, which produced no monazite in 1986.

Measured reserves of monazite in 1987 were 36,806 tons. Estimated rare-earth oxide content based on these reserves was 18,376 tons. Monazite reserves were located in the States of Bahia, Espírito Santo, Minas Gerais, and Rio de Janeiro.[18]

Production of rare-earth compounds, as reported by the Government in 1987, was 22,500 kilograms of rare-earth carbonate, 2,422,000 kilograms of rare-earth chloride, and 66,000 kilograms of rare-earth oxides.[19]

Companhia Vale do Rio Doce (CVRD) planned to construct a rare-earth separation plant at Araxa, Minas Gerais, utilizing separation technology from Japan's Mitsubishi Corp. The company reportedly will be able to produce 3,000 tons of REO per year as byproducts from its titanium operation at Tapira.[20]

Canada

Yttrium concentrate production in 1989 from uranium ores at the Elliot Lake Mine in Ontario, on an yttrium oxide content basis, increased from 50 tons to 100 tons. The yttrium operations were a joint venture of Unocal Canada Ltd., SM Yttrium Ltd., and Denison Mines Ltd.[21]

Joint-venture partners Hecla Mining Co. and Highwood Resources Ltd. decided not to develop the Thor Lake beryllium-niobium-rare-earth deposit in the Northwest Territories because of poor market outlook. The deposit reportedly contained 8,600 tons of yttrium oxide along with other rare earths.

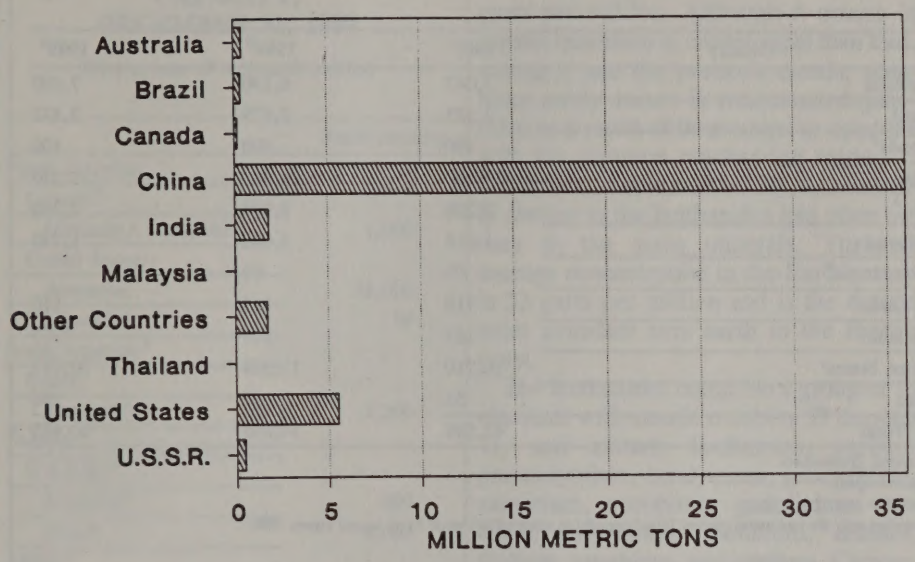
China

China remained the world's leading producer of rare earths despite reduced output from southern mines.[22] Decreased production was reportedly caused by a drop in domestic and foreign demand during the second half of 1989. Production of various mixed and separated rare-earth products reportedly reached 19,670 tons of equivalent

FIGURE 3

WORLD RESERVES OF RARE EARTHS

(REO CONTENT)



REO, an increase of 5.4% from 1988's level. Growth sectors for the rare earths in China were petroleum cracking catalysts, agricultural fertilizers, permanent magnets, and phosphors.

Scandium was produced at five locations in China and refined at four locations as follows:[23]

Scandium mine locations
1. Jiangxi Province, tungsten mines
2. Guangxi Province, tin mines
3. Guangdong Province, tin mines
4. Fujian Province, iron (magnetite) mines
5. Zhejian Province, tungsten and beryllium mines

Scandium processor locations	Principal product
1. Jiangxi Province Guizhou Cobalt Smelter	Tungsten
2. Guangxi Province, Pingkwa	NA
3. Hunan Province, Taujian, Rare-Earth Metal Smelter	NA
4. Hunan Province, Hunan Rare-Earth Metal Research Institute	Tin

NA Not available.

Denmark

Morstral Minerals investigated a heavy-mineral sands deposit near Hanstholm, northern Jutland. The deposit, covering 100 square kilometers, contains the minerals ilmenite, rutile, zircon, and monazite.[24]

Greenland

Hecla Mining Co. (47%), Nuna Oil (50%), and Gewerkschaft Wilhelm Bergbaugesellschaft (3%) formed a consortium, named Sarfartoq, to explore for rare earths and niobium in southeastern Greenland.[25]

Others, including A/S Carl Nielsen of Denmark and a Canadian triventure composed of Platinova Resources Ltd. (40%), Highwood Resources Ltd. (30%), and Aber Resources Ltd. (30%), explored a banded nepheline syenite (kakortokite) in the Ilimaussaq intrusive complex that contains the rare-earth and zirconium-bearing mineral eudialyte.[26]

Guyana

An estimated 450 river-based diamond and gold dredges were reportedly processing heavy-mineral-containing resources. Other heavy minerals identified as potential byproducts of the dredging operations were ilmenite, rutile, zircon, and, in some deposits, monazite.[27]

Japan

Japanese demand for scandium was primarily for metal halide lamps, consuming about 50%. An estimated 30% is consumed in gadolinium-scandium-gallium garnets (GSGG) and the balance consumed in the electron guns of CRT's, automotive catalysts, and other uses.[28]

Madagascar

QIT-Fer et Titane Inc. (QIT), a subsidiary of RTZ Corp. PLC (RTZ), announced that its joint-venture heavy-mineral sands project would be delayed at least until 1995, a result of problems encountered in negotiations with the Government.

Malawi

The French group, BRMG, investigated the well-known Kangankunde Hill rare-earth carbonatite in 1988, and was reportedly preparing a prefeasibility report.[29] Monazite in the carbonatite was environmentally acceptable because of its low thorium oxide content, 0.08%.

New Zealand

Fletcher Titanium Products Ltd. started production of heavy minerals at a pilot plant located on the west coast of South Island at yearend. Production of 400 tons per year of rutile, zircon, and monazite was planned.[30]

South Africa, Republic of

General Mining Corp. Ltd. continued to produce byproduct monazite from its Naboomspruit fluorspar operations in the Transvaal. Monazite reportedly was separated during processing of the fluorspar by wet high-intensity magnetic separators.[31]

The Anglo American Corp. of South Africa Ltd. studied the feasibility of developing heavy-mineral sand deposits in Namaqualand. The deposits were on lands owned by De Beers Consolidated Mines near the west Cape coast, 30 miles north of the Olifants River. A wet concentration pilot plant was operated during the year. If a decision is made to proceed with the project, production was planned to commence in 1992, with an expected monazite output of 1,000 tons per year. Rutile and zircon production were expected to be

25,000 and 100,000 tons per year, respectively.[32]

Severin Mining and Development Co. (Pty.) Ltd. conducted pilot plant tests on samples of a deposit 30 miles south of Richards Bay at Mitunzini. The deposit resembled the Richards Bay deposit and was reported to have a 10% heavy-mineral grade. A decision was expected in early 1990, following completion and analysis of pilot plant tests.[33]

Richards Bay Minerals reportedly delayed exploration and development work on its project at Lake St. Lucia in the Natal Province because of environmental concerns.[34]

Rio Tinto Minerals Development Ltd., a subsidiary of RTZ, acquired total ownership of QIT from BP Minerals Development Ltd., a subsidiary of British Petroleum. QIT holds a 50% interest in Richards Bay Minerals in the Republic of South Africa.[35]

Taiwan

Pacific Ocean Rare Earth Industry Co. (POR), continued production of heavy minerals, including monazite, on the west coast. Monazite reserves in Yuanlin and Chiai Counties were 50,000 tons. Ore from the area was shipped to Hsinchu for processing and separation of the rare earths from monazite. The POR rare-earth plant at Hsinchu was capable of processing 1,000 tons of monazite per year with annual separation capacity as follows: lanthanum oxide, 100 tons; cerium oxide, 240 tons; didymium oxide (Pr-Nd), 100 tons; samarium oxide, 12 tons; europium oxide, 2 tons; mixed gadolinium-terbium-dysprosium oxide, 20 tons; and yttrium oxide, 4 tons.[36]

Thailand

The Office of Atomic Energy for Peace of Thailand was building a rare-earth separation plant to process 300 tons of monazite per year. The plant was scheduled for completion in late 1990.[37]

CURRENT RESEARCH

Carr Boyd Minerals Ltd. reported a breakthrough in beneficiation of the rare earths. Company-funded research at the University of Western Australia discovered that mixed rare earths could be mechanically separated from the ore using high-energy ball mills instead of conventional chemical treatment. Rare earths produced from the new process can reportedly be reduced directly to mischmetal or alloyed simultaneously without prior melting or heating.[38]

Magnesium Elektron announced the development of a new rare-earth-magnesium alloy as a replacement for certain magnesium-thorium alloys. The new alloy, WE43, contains 3.75% to 4.05% yttrium, 2% to 2.5% neodymium, 0.75% to 1.25% heavy rare earths, a minimum 0.3% zirconium, and the balance magnesium. The alloy can reportedly substitute for the magnesium-thorium alloys presently used in several aerospace applications.[39]

Researchers at the Aluminum Company of America created a high-temperature aluminum alloy using a rare earth. The rapidly cooled cerium-iron-aluminum alloy had an extremely fine-grained microstructure, in the 5 to 40 micron range. Designated Cu78, the new alloy reportedly has improved strength and fracture toughness up to 349° C. Cu78 was expected to be used in airframe structural parts and other aerospace components.[40]

TABLE 6

RARE EARTHS: WORLD MINE PRODUCTION, BY COUNTRY

(Metric tons of REO equivalent)

Country	1987	1988[p]	1989[e]
Australia	7,047	6,530	7,400
Brazil	2,383	2,475	2,475
Canada[e]	100	100	100
China	15,100	29,640	[1]25,220
India[e]	2,200	2,200	2,200
Malaysia	1,618	1,630	1,730
Mozambique[e]	([2])	([2])	—
Sri Lanka[e]	110	110	110
Thailand	267	375	[1]365
United States[3]	16,710	11,533	[1]20,787
Zaire	53	92	[1]96
Total	45,588	54,685	60,483

[e]Estimated. [p]Preliminary.
[1]Reported figure.
[2]Revised to zero.
[3]Comprises only the rare earths derived from bastnasite as reported in Unocal Corp. annual report, 1989.

OUTLOOK

The outlook for rare earths was promising. Exhibiting a wide range of chemical and physical properties, the rare earths have found increased use in an expanding number of applications. The demand pattern was expected to continue to favor separated high-purity products. Although a few traditional markets have been in decline (petroleum cracking catalysts and mixed metallurgical additives), increased rare earth use is expected in the near-term in permanent magnets, automotive catalytic convertors, glass additives, and industrial, medical, and communications lasers. Recent advancements in high-temperature superconductor technology indicate a large potential for long-term growth.

World supplies of rare earths are expected to be adequate to meet demand, in part because increased demand for titanium and zirconium minerals has initiated expansions in both the mining and processing sectors. Australia, China, and the United States should continue as the principal sources of supply.

Economic projections forecast only a modest advance in the economy in 1990, followed by a resurgence of consumer demand in 1991.[41] Rare-earth demand is predicted to outperform the domestic economy in 1990, especially in the non-traditional markets. Continued diversification in rare-earth markets is expected to provide increased stability to the industry.

BACKGROUND

Definition, Grades, and Specifications

The rare earths are a group of 17 elements comprised of scandium, yttrium, and the lanthanides.

TABLE 7

WORLD ANNUAL RARE-EARTH MINERAL PRODUCTION CAPACITY, DECEMBER 31, 1989

(Metric tons of rare-earth oxides)

	Rated capacity
North America:	
Canada:[e]	
Monazite,[1] brannerite[2]	1,000
United States:	
Bastnasite	26,000
Monazite[1]	W
South America:[e]	
Brazil:	
Monazite[1]	2,200
Europe:	
U.S.S.R.:[e]	
Monazite[3]	500
Other[4]	1,000
Africa:[e]	
Mozambique:	
Monazite[5]	2
South Africa, Republic of:	
Monazite[1]	NA
Monazite[4]	NA
Zaire:	
Monazite[4]	55
Asia:	
China:[e]	
Bastnasite[6]	20,000
Monazite[1]	10,000
Xenotime[1]	50
Other[7]	1,000
India:[e]	
Monazite[1]	2,200
Malaysia:[e]	
Monazite[5]	3,300
Xenotime[5]	600
Sri Lanka:[e]	
Monazite[1]	110
Thailand:[e]	
Monazite[5]	1,100
Xenotime[5]	75
Oceania:	
Australia:	
Monazite[1]	11,000
Xenotime[1]	20
World total (rounded)	91,000

[e]Estimated. NA Not available. W Withheld to avoid disclosing proprietary data.
[1]Byproduct of processing for titanium and zirconium minerals.
[2]Byproduct of processing for uranium, recovered as yttrium concentrate.
[3]Byproduct of processing for gold.
[4]Byproduct of processing for phosphate rock.
[5]Byproduct of processing for tin minerals.
[6]Byproduct of processing for iron minerals.
[7]Residual weathering product in clay.

Scandium, atomic number 21, is the lightest rare-earth element. It is the 31st most abundant element in the Earth's crust with an average crustal abundance of 22 parts per million. Although it occurs in greater quantities in crustal rocks than lead, mercury, and the precious metals, scandium rarely occurs in concentrated quantities as a result of its aversion to combine with the common ore-forming anions.

Yttrium, atomic number 39, is chemically similar to the lanthanides and often occurs in the same minerals. Yttrium's average concentration in the Earth's crust is 33 parts per million and is the second most abundant rare earth in the Earth's crust.

The lanthanides comprise a group of 15 elements with atomic numbers 57 through 71, and include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Cerium, the most abundant of the group at 60 parts per million, is more abundant than copper. Thulium, the least abundant of the lanthanides at 0.48 parts per million, occurs in the Earth's crust in higher concentrations than thallium, antimony, cadmium, and bismuth.

Largely because of differing ionic radii, the rare-earth elements are broadly classified into two groups: the light or cerium subgroup, comprised of the first seven lanthanides (atomic numbers 57 through 63), and the heavy or yttrium subgroup, comprised of the remaining lanthanides and yttrium (atomic numbers 64 through 71 and 39, respectively). Yttrium is classed with the heavy subgroup because of its occurrence, ionic radius, and other similar properties.

Bastnasite can theoretically contain 74.81% REO.[42] Flotation concentrates of bastnasite average 60% REO, which can be upgraded to 70% REO by acid leaching, and to 85% REO by a combination of acid leaching and calcining.

Monazite theoretically can contain 69.73% REO. Monazite concentrate is usually sold at 55% minimum REO contained plus thorium, with most product grading 59% to 65% REO. Thorium contents are variable, but typically occur in the range of 4% to 10% equivalent thorium oxide. Monazite with a low thorium content commands a premium price.

Xenotime can theoretically contain 61.40% yttrium oxide. However, xenotime concentrates from Southeast Asia and Australia typically contain 25% to 30% yttrium oxide. Xenotime is often upgraded by acid leaching to produce an yttrium concentrate grading 60% yttrium oxide and the balance primarily other rare earths.

The term "mischmetal" is used to denote a mixture of rare-earth elements in metallic form. It generally has the same ratio of rare-earth elements as that found in the ore. Ferrocerium is a pyrophoric alloy of mischmetal and iron. Rare-earth silicide is an alloy containing about one-third mischmetal, one-third iron, and one-third silicon. The rare-earth content in master alloys ranges from tenths of a percent in nodularizing alloys for ductile iron to 10% or more in inoculants for gray cast iron. Alloys containing nearly 100% rare-earth metals, such as mischmetal, are additives to certain steels.

The purity of separated rare-earth elements, produced primarily by solvent extraction or ion exchange, usually grade 96% or higher in purity. High-purity rare-earth compounds and metals are produced up to 99.9999% purity. Rare-earth products grading higher than 99.9% purity are often produced to specification. As a result of the wide range of products in which rare earths are consumed, many grades of rare-earth concentrates, compounds, alloys, and metals are marketed. Analyses of the rare-earth contents of selected ores are shown in table 8.

Industry Structure

Rare-earth ore minerals are sold by producers directly to processors, consumers, and commodity brokers, usually as a concentrate. Of the three principal ore minerals bastnasite, monazite, and xenotime, only bastnasite concentrate may be used in certain industrial applications with little or no processing. Most rare-earth concentrates undergo extensive processing to produce mixed or separated compounds and metals. Few companies in the rare-earth industry are fully integrated. Most companies that mine rare earths sell their concentrates to processors that separate the rare earths by chemical processing, primarily solvent extraction or ion exchange. Processors producing separated rare-earth products are often partially integrated, manufacturing fabricated and semifabricated products that are sold directly to manufacturers or end users. The distribution of the global mining industry is illustrated in figure 7.

TABLE 8

RARE-EARTH CONTENTS OF MAJOR SOURCE MINERALS

(Percent of total rare-earth oxide)[1]

Rare earth	Bastnasite Mountain Pass, California, USA[2]	Bastnasite Nei Monggol, China[3]	Monazite Capel, Western Australia[4]	Monazite North Stradbroke Island, Queensland, Australia[5]	Monazite Green Cove Springs, Florida, USA[6]	Monazite Nangang, Guangdong, China[7]
Lanthanum	33.2000	23.000	23.8938	21.5000	17.5000	23.0000
Cerium	49.1000	50.0000	46.0177	45.8000	43.7000	42.7000
Praseodymium	4.3400	6.2000	5.0442	5.3000	5.0000	4.1000
Neodymium	12.0000	18.5000	17.3805	18.6000	17.5000	17.0000
Samarium	.7890	.8000	2.5310	3.1000	4.9000	3.0000
Europium	.1180	.2000	.0531	.8000	.1600	.1000
Gadolinium	.1660	.7000	1.4867	1.8000	6.6000	2.0000
Terbium	.0159	.1000	.0354	.2900	.2600	.7000
Dysprosium	.0312	.1000	.6903	.6400	.9000	.8000
Holmium	.0051	trace	.0531	.1200	.1100	.1200
Erbium	.0035	trace	.2124	.1800	trace	.3000
Thulium	.0009	trace	.0177	.0300	trace	trace
Ytterbium	.0006	trace	.1239	.1100	.2100	2.4000
Lutetium	.0001	trace	.0354	.0100	trace	.1400
Yttrium	.0913	.5000	2.4071	2.5000	3.2000	2.4000
Total	99.8615	100.1000	99.9823	100.7800	100.0400	98.7600

	Monazite Southwest Coast Taiwan[8]	Xenotime Lahat, Perak, Malaysia[2]	Xenotime Southeast Guangdong, China[9]	RE minerals in clay Xunwu, Jiangxi Province[10]	RE minerals in clay Longnan, Jiangxi Province[10]	RE in uranium residues Elliot Lake, Ontario, Canada[11]
Lanthanum	20.0000	1.2400	1.2000	43.3700	1.8200	.8000
Cerium	46.0000	3.1300	3.0000	2.3800	.3700	3.7000
Praseodymium	5.0000	.4930	.6000	9.0200	.7400	1.0000
Neodymium	20.0000	1.5900	3.5000	31.6500	3.0000	4.1000
Samarium	3.7000	1.1400	2.2000	3.9000	2.8200	4.5000
Europium	.5800	.0120	.2000	.5000	.1200	.2000
Gadolinium	2.0000	3.4700	5.0000	3.0000	6.8500	8.5000
Terbium	.3000	.9060	1.2000	trace	1.2900	1.2000
Dysprosium	.4500	8.3200	9.1000	trace	6.6700	11.2000
Holmium	.0900	1.9800	2.6000	trace	1.6400	2.6000
Erbium	—	6.4300	5.6000	trace	4.8500	5.5000
Thulium	.9800	1.1200	1.3000	trace	.7000	.9000
Ytterbium	—	6.7700	6.0000	.2600	2.4600	4.0000
Lutetium	—	.9880	1.8000	.1000	.3600	.4000
Yttrium	.9000	61.0000	59.3000	8.0000	65.0000	51.4000
Total	100.0000	98.5890	102.6000	102.1800	98.6900	100.0000

[1]Some analyses previously adjusted to 100%.

[2]Johnson, G. W. and T. E. Sisneros. Analysis of Rare-Earth Elements in Ore Concentrate Samples Using Direct Current Plasma Spectrometry. Proceedings of the 15th Rare-Earth Research Conference, Rolla, Mo, June 15-18, 1981. The Rare Earths in Modern Science and Technology, Plenum Press, NY, v. 3, 1982, pp. 525-529.

[3]Zang, Z., et al. Rare-Earth Industry in China. Hydrometallugy, v. 9, No. 2, 1982, pp. 205-210.

[4]Westralian Sands Ltd. Company Brochure. Product Specifications.

[5]Analysis from Consolidated Rutile Ltd.

[6]Analysis from Associated Minerals, Green Cove Springs, FL.

[7]Xi, Zhang. The Present Status of Nd-Fe-B Magnets in China. Paper presented at The Impact of Neodymium-Iron-Boron Materials on Permanent Magnet Users and Producers Conf. Gorham International Inc., Clearwater, FL, Mar. 2-4, 1986, 5 pp.

[8]Lu, Daluh, Horng, J., and C. Tung. The Separation of Europium from Taiwan Black Monazite. In the Proceedings of the ClChE-AlChE Symposium on Modern Chem. Eng. Tech., Taipei, Taiwan, Sept. 16-19, 1986, pp. 57-59.

[9]Nakamura, Shigeo. China and Rare Metals-Rare Earth. Ch. in Industrial Rare Metals, No. 94, May 1988, pp. 23-28.

[10]Introduction to Jiangxi Rare-Earths and Applied Products. Jiangxi Province Brochure at the International Fair for Rare Earths, Beijing, China, Sept. 1985, 42 pp. (In English and Chinese).

[11]Trends in Usage of Rare-Earths. National Materials Advisory Board. Pub. NMAB-226, Washington, DC, Oct. 1970, 67 pp.

FIGURE 4

BASTNASITE
(PERCENT REO)

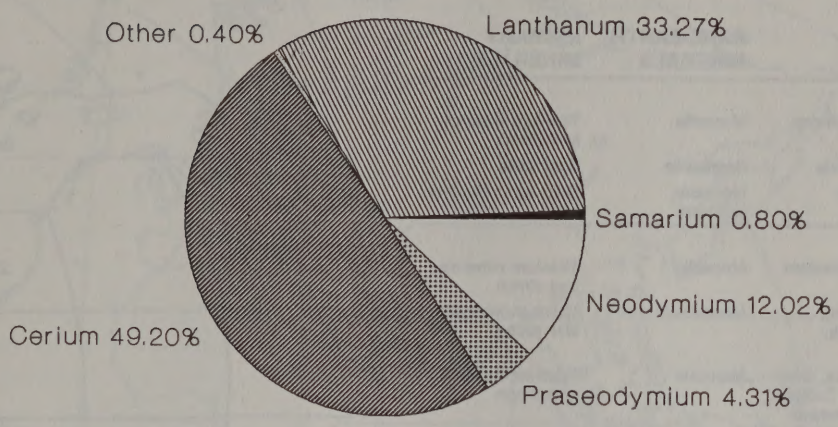
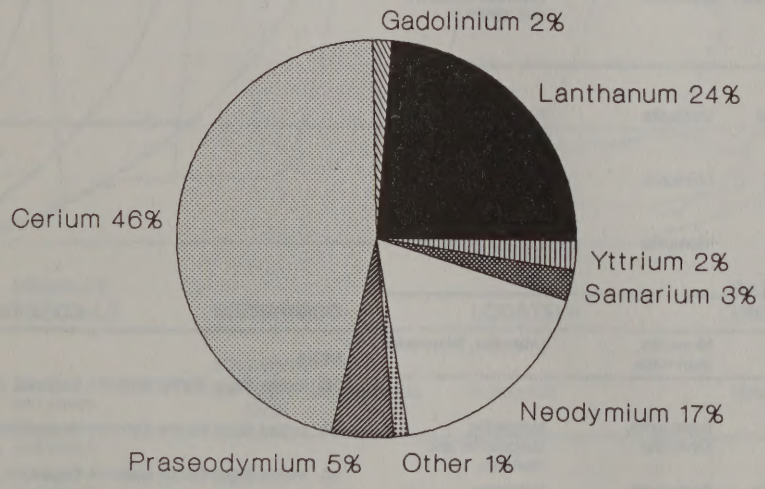
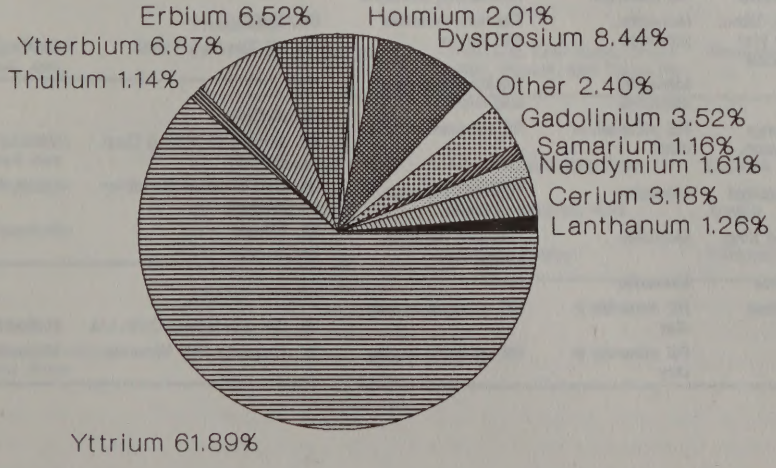


FIGURE 5

MONAZITE
(PERCENT REO)



XENOTIME
(PERCENT REO)



Geology-Resources

Although the rare-earth elements are essential constituents in more than 100 minerals, only bastnasite, monazite, xenotime, and rare earth-bearing clay occur in concentrations high enough to be considered economic ore deposits. Other rare-earth-bearing minerals such as eudialyte, an yttrium-bearing zirconium silicate, may be considered an economic resource at some time in the future.

Monazite and xenotime originate as primary accessory minerals in many crustal rocks. Erosion of the crust breaks down the crust-forming rocks releasing monazite, xenotime, and other minerals. Eroded alluvial material then undergoes natural separation and sorting by rain and wind and dissolution of the soluble minerals. Further separation and concentration of heavy minerals, especially by specific gravity, is accomplished primarily by river and sea currents. Only the more chemically and physically stable minerals, including monazite and xenotime, survive transport to become concentrated in an economic heavy-mineral deposit.

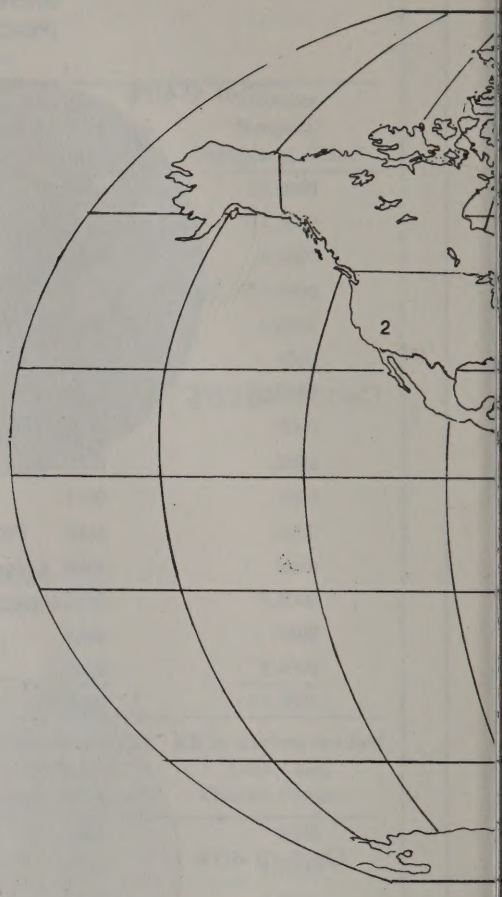
Bastnasite occurs in greater abundance in crustal rocks than do monazite or xenotime. It is most frequently associated with rocks termed carbonatites. This name is derived from the high number of carbonate (e.g., calcite) minerals that make up the composition of the rock. Unlike sea shells, which form calcite from calcium and carbon dioxide taken from seawater, these carbonate minerals arise from molten magma originating from beneath the crust. The magma intrudes the crust at points of weakness and begins to crystallize as it ascends because of decreases in pressure and temperature. As crystallization (i.e., rock forming) progresses, the once-molten magma becomes increasingly more viscous, and the rise toward the surface is halted. If the carbonatite occurs at or near the surface at a sufficient grade it may be economic.

Technology

Exploration and Development.—The Mountain Pass deposit was discovered during exploration for radioactive minerals, a property typical of most rare-earth minerals or those associated with them. Exploration techniques employed to locate the rare earths include surface and airborne reconnaissance with magnetometric and radiometric equipment. It should be noted,

FIGURE 7

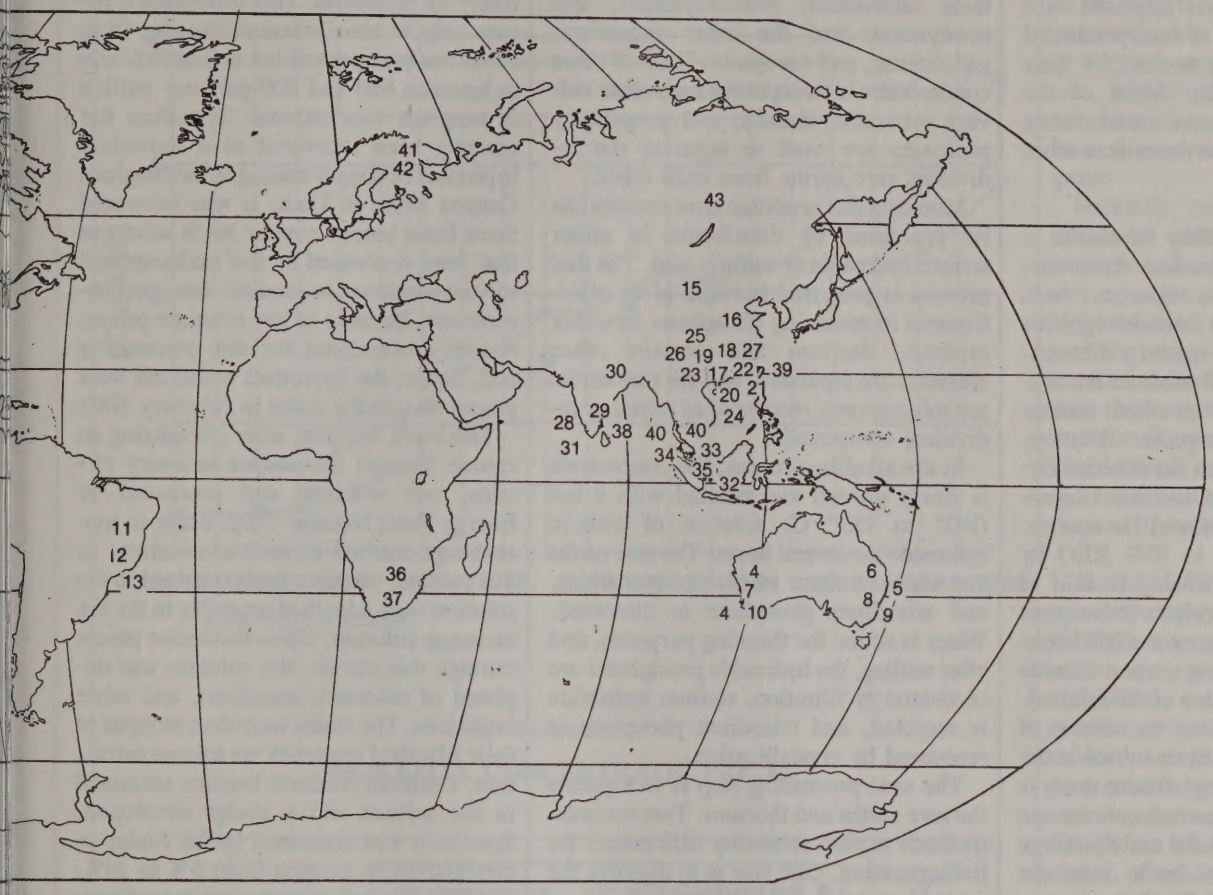
PRINCIPAL WORLD RARE-EARTH



COMPANY	LOCATION	RARE-EARTH MINERALS	PRIMARY MINERALS
UNITED STATES			
1. Associated Minerals (USA) Inc.	Green Cove Springs, Florida	Monazite	Titanium minerals and zircon
2. Molycorp, Inc.	Mountain Pass, California	Bastnasite	Bastnasite
3. Imperial Mining Co.	Marion, North Carolina	Monazite, xenotime	Gold and industrial sand and gravel
AUSTRALIA			
4. Associated Minerals Consolidated Ltd.	Capel and Eneabba, Western Australia	Monazite	Titanium minerals and zircon
5. Consolidated Rutile Ltd.	Amity, Bayside, Gordon, Dunwich, and Pinkenba, Queensland	Monazite	Titanium minerals and zircon
6. Currumbin Minerals Pty. Ltd.	Kirra, Kingscliff, Gympie, Gold Coast, Rainbow Beach, Cudgen, and Currumbin, Queensland	Monazite	Titanium minerals and zircon
7. Cable Sands (WA) Pty. Ltd.	North Capel, Waroona, and Bunbury, Western Australia	Monazite, xenotime	Titanium minerals and zircon
8. Mineral Deposits Ltd.	Stockton and Durness (Tea Gardens), New South Wales	Monazite	Titanium minerals and zircon
9. RZ Mines (Newcastle) Pty. Ltd.	Tomago and Nabiac, New South Wales	Monazite	Titanium minerals and zircon
10. Westralian Sands Ltd.	Yoganup (Yoganup Extended), Boyanup (Yoganup North), and Capel (North Capel), Western Australia	Monazite	Titanium minerals and zircon
BRAZIL			
11. Nuclebras de Monazita e Associados Ltda. (NUCLEMON)	Alcobaca, Porto Seguro, and Prado, Bahia	Monazite	Titanium minerals and zircon
12. Nuclebras de Monazita Associados Ltda. (NUCLEMON)	Aracruz, Guarapari, and Itapemirim Espirito Santo	Monazite	Titanium minerals and zircon
13. Nuclebras de Monazita e Associados Ltda. (NUCLEMON)	Sao Joao da Barra, Rio de Janeiro	Monazite	Titanium minerals and zircon
CANADA			
14. Denison Mines Ltd.	Elliot Lake, Ontario	Monazite, brannerite	Uraninite, brannerite
CHINA			
15. State-owned	Baiyunebo, Inner Mongolia Autonomous Region	Bastnasite, monazite	Magnetite, specularite and hematite
16. State-owned	Weishan, Shandong Province	Bastnasite	Unknown
17. State-owned	Longnan, Xunwu, and Dingnan, Jiangxi Province	RE minerals in clay	RE minerals in clay
19. State-owned	Xihuashan, Jiangxi Province	RE minerals	Wolframite, scheelite
20. State-owned	Yangjiang (Nanshanhai), Xitou, Dianbai, Zhanjiang, and Haikang, Guangdong Province	Monazite, xenotime	Titanium minerals and zircon
21. State-owned	Nangang, Guangdong Province	Monazite, xenotime	Titanium minerals and zircon
22. State-owned	Pingyuan, Qingyuan, Longchuan Heping, and Ruyuan, Guangdong Province	RE minerals in clay	RE minerals in clay
23. State-owned	Qinzhou and Beihai, Guangxi Province	Monazite	Titanium minerals and zircon
24. State-owned	Sai-Lao, Wuzhaung, and Xinglong, Hainan Island	Monazite	Titanium minerals and zircon
25. State-owned	Yueyang, Hunan Province	Monazite	NA
26. State-owned	Tongsalin, Hunan Province	RE minerals in clay	RE minerals in clay
27. State-owned	Fujian Province	RE minerals in clay	RE minerals in clay

COMPANY	LOCATION
INDIA	
28. Indian Rare Earths Ltd.	Chavara, Alwaye, Kerala
29. Indian Rare Earths Ltd.	Manavalakurichi, Tamil Na
30. Indian Rare Earths Ltd.	Chatrapur, Orissa
31. Kerala Minerals & Metals Ltd.	Chavara, Kerala
INDONESIA	
32. PT Tambary Timah	Belitung, Bangka,and Singkep, Sumatra
MALAYSIA	
33. Malaysian Mining Corp. Berhad	Various locations in Perak and Selangor States
34. Beh Minerals Sendirian Berhad	Lahat, Perak
35. Others	Various locations
SOUTH AFRICA	
36. General Mining Corp. Ltd.	Naboomspruit, Tranavaal
37. Richards Bay Minerals	Richards Bay, Natal

MINERAL PRODUCERS



RARE-EARTH MINERALS	PRIMARY MINERALS
onazite	Titanium minerals and zircon
onazite	Titanium minerals and zircon
onazite	Titanium minerals and zircon
onazite	Titanium minerals and zircon
onazite, notime	Cassiterite
onazite, notime	Cassiterite
onazite, notime	Cassiterite
onazite, notime	Cassiterite
onazite	Fluorite
onazite	Titanium minerals and zircon

COMPANY	LOCATION	RARE-EARTH MINERALS	PRIMARY MINERALS
SRI LANKA			
38. Ceylon Mineral Sands Corp.	Pulmoddai	Monazite	Titanium minerals and zircon
TAIWAN			
39. Pacific Ocean Rare Earth Industry Co.	Yuanlin and Chiai Counties	Monazite	Ilmenite and zircon
THAILAND			
40. Various companies	Prachuap Khiri Khan, Chumphon, Phuket, and Takua Pa	Monazite	Cassiterite
U.S.S.R			
41. State owned	Lovozero complex, Kola Peninsula	Loparite	Apatite
42. State-owned	Khibiny complex, Kola Peninsula	Apatite	Apatite
43. State-owned	Synnyr, Khrebet	Bastnasite	NA

however, that very little exploration is conducted specifically for rare earths. Two world-class bastnasite deposits are developed and dozens of heavy mineral sand deposits are being worked for their combined mineral suite. Most of the mineral sand deposits were found during exploration conducted for ilmenite or other titanium minerals.

Mining.—Mountain Pass bastnasite is mined as a primary product from carbonatite, an intrusive igneous rock associated with alkaline intrusive igneous rocks. The hard rock is mined via bench-cut, open pit methods. Blasted ore is trucked to the mill where it is crushed, screened, and heated to improve flotation. Bastnasite recovered from the flotation circuit is thickened, filtered, and dried to produce a 60% REO concentrate. The concentrate can be upgraded to 70% REO by leaching with 10% hydrochloric acid to consume any remaining calcite. Subsequent roasting can further increase the REO content to 85% by liberating carbon dioxide from the carbonate portion of the mineral.

Heavy-mineral sands are the sources of most monazite and xenotime mined in the world. Almost all mining of these sands is done by floating dredges that concentrate the heavy minerals onboard and discharge the unwanted tailings back into the previously mined areas. Dredging is particularly well-suited for the mining of unconsolidated sands. Dredged ore is mined with either cutter-head suction dredges or bucketwheel excavators. The onboard wet mill separates the economic heavy minerals ("heavies") from the gangue through a series of equipment that may include hydrocyclones, screens, spirals, and cones. Indurated sand deposits that are too difficult to extricate by dredging are mined with typical earth-moving equipment (e.g., dozers, loaders, and/or scrapers).

Processing.—Bastnasite is processed by leaching 85% REO roasted calcine with hydrochloric acid to yield soluble chlorides. Cerium, oxidized during roasting to a higher valence, is insoluble and passes through a countercurrent decantation and thickening circuit. The thickened material is then filtered to collect the precipitate, containing about 70% REO, 90% of which is ceric oxide, which is dried and sold as cerium concentrate. The leach solution overflowing the thickener circuit contains the remaining rare earths in the form of chlorides and is put through a solvent extraction process to separate the rare earths into two concentrates. One contains lanthanum, praseodymium, and neodymium and the other samarium, gadolinium, and europium. Each of these concentrates is then put through other solvent extraction circuits, and proprietary processes are used to separate the individual rare earths from each other.

Monazite and xenotime concentrates can be processed by dissolution in either sodium hydroxide or sulfuric acid. The first process is preferred because of its effectiveness in removing phosphate. In either method, thorium and certain other elements are separated, and the rare earths are subsequently recovered as mixed or individual compounds.

In the alkaline process, the concentrate is finely ground and reacted with a hot (140° to 150° C) solution of sodium hydroxide for several hours. The rare earths and thorium form insoluble hydroxides, and trisodium phosphate is dissolved. Water is added for thinning purposes, and after settling, the hydroxide precipitates are recovered by filtration, sodium hydroxide is recycled, and trisodium phosphate is recovered by crystallization.

The next processing step is to separate the rare earths and thorium. Two common methods exploit solubility differences for the separation. One way is to dissolve the mixed hydroxides in nitric or hydrochloric acid. Thorium can then be selectively precipitated by partially neutralizing the solution with the addition of sodium hydroxide or ammonium hydroxide. The solution is filtered to remove the thorium precipitate. Another method selectively dissolves the rare-earth hydroxides in hydrochloric acid. Rare-earth chlorides are dissolved, and thorium hydroxide is precipitated and separated by filtration. Solvent extraction also may be employed to separate the two materials. Tri-butyl phosphate or certain amine nonaqueous solvents can be used, but amine extractants are reported to perform best in sulfate solutions and form a high-purity thorium complex.

In the acid digestion process, monazite is finely ground and reacted with concentrated sulfuric acid at about 200° C. Temperature and acid concentration are controlled during digestion, and both rare-earth and thorium sulfates are formed. The sulfates are then dissolved in water and separated from the insoluble impurities by filtration. Thorium is then separated by precipitating with ammonia.

Byproduct Scandium.—There is no domestic exploration or mining conducted solely for scandium. This is because it occurs only in trace amounts ranging from about one part per million in uranium ores to between 500 and 800 part per million in tungsten concentrates. Scandium has recently been recovered as a secondary byproduct of copper mining at the Bingham Canyon Mine in Utah. It was recovered there from barren copper leach solutions that were processed by ion exchange and solvent extraction to produce uranium concentrates. Because of low uranium prices, recovery operations for this commodity and, hence, the byproduct scandium were placed on standby status in February 1989.

The leach solution, after completing its course through the copper recovery circuits, was obtained and processed by Energy Fuels Nuclear Corp. using an ion-exchange method to recover uranium. In this method, metal cations contained in the solution were adsorbed on resins in the ion exchange columns. Upon successive passes through this circuit, the solution was depleted of uranium, scandium, and other impurities. The resins were then stripped of their adsorbed materials via solvent extraction. Uranium products became entrained in the solvent and a sludge developed. Scandium was contained in the sludge in concentrations ranging from 5% to 10%. The sludge was then processed at a refinery to recover scandium oxide or other specific compound products.

Economic Factors

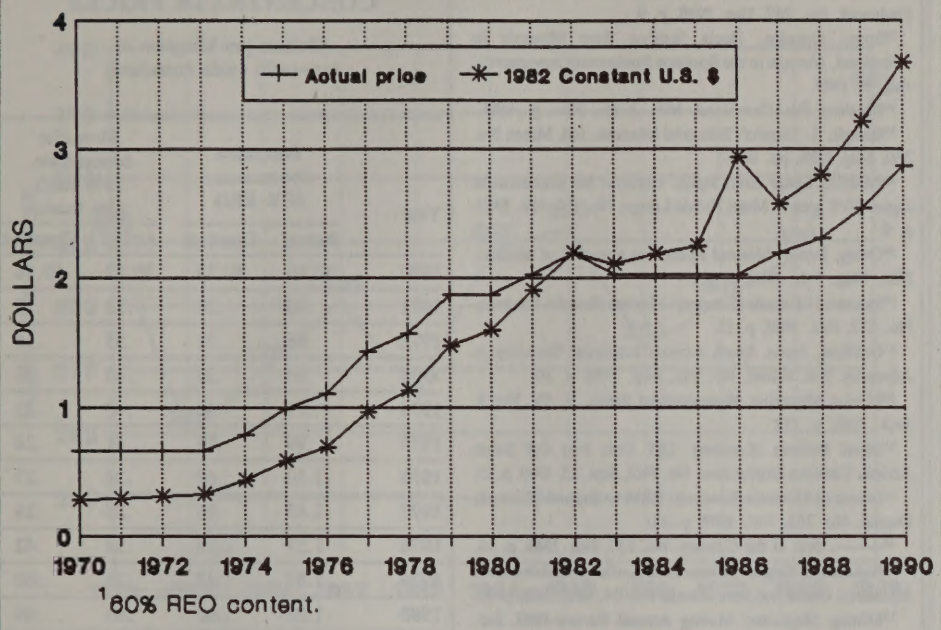
Prices.—Trends for bastnasite and monazite concentrate prices are shown in figures 8 and 9. Both concentrates exhibited a fairly steady growth in prices except for a few years following the 1979-81 economic recession. Time-price relationships, based on 1982 constant dollars, are shown in table 9.

Tariffs.—In 1989, the classification of imports to the United States was revised under the Harmonized Tariff Schedule of the United States. The new system of classification was enacted to facilitate trade between the United States and the rest of the world. The tariffs on imported rare-earth materials are shown in table 10.

Depletion Provisions.—The U.S. Government's tax depletion allowance on domestically produced monazite was 22% on the thorium content and 14% on the

FIGURE 8

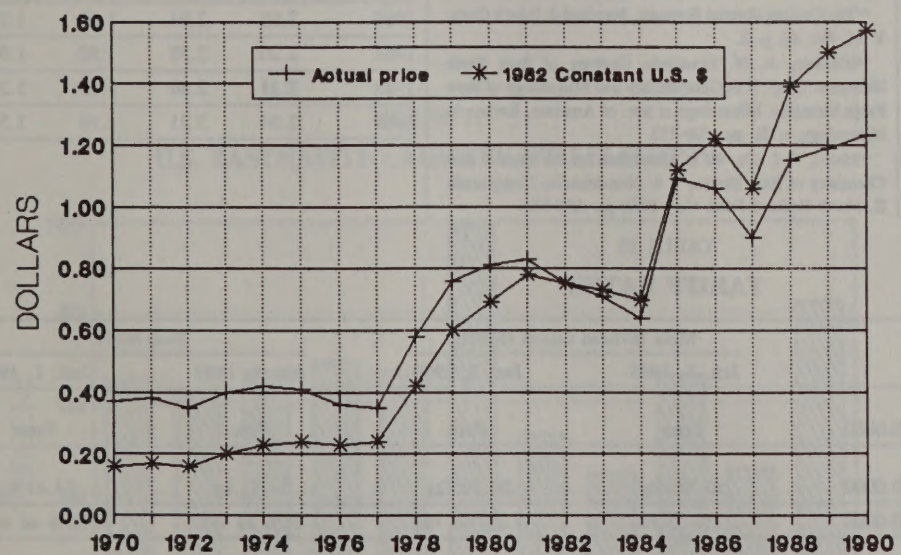
BASTNASITE CONCENTRATE[1] PRICES



[1]60% REO content.

FIGURE 9

MONAZITE CONCENTRATE[1] PRICES



[1]55% REO content.

rare-earth content. Monazite produced in foreign countries was permitted a 14% depletion allowance. The domestic depletion allowance for U.S. and foreign produced bastnasite and xenotime was 14%.

Operating Factors

Environmental Requirements.—Domestic mines and processing plants were required to meet Federal and State environmental guidelines for air, water, and soil quality. Reclamation of land currently mined for materials other than coal, including rare earths, was controlled by State authority. Requirements differed by State jurisdiction, with most requiring the mined land be returned to its original use or transformed into recreational and agricultural areas.

Naturally radioactive thorium-bearing rare-earth minerals and their byproducts were controlled by Federal and State regulatory agencies. State requirements differed by jurisdiction, but typically controlled the handling, shipping, and storage of materials containing thorium. Thorium-bearing residues were required to be disposed of only in Federally licensed fee-for-burial sites. The domestic rare-earth industry has incurred substantial costs to properly store and dispose of radioactive waste products.

Toxicity.—The rare-earth elements are considered only slightly toxic.[42] However, the production of skin and lung granulomas after exposure to oxides, fluorides, chlorides, and metals by prolonged breathing, intradermal injection, or subcutaneous implantation requires extensive protection to prevent exposure through cuts and abrasions of the skin and inhalation. Symptoms of toxicity include writhing, ataxia, labored respiration, walking on the toes with arched back, and sedation. Research has shown males are less susceptible than females to the toxic effects of the rare earths. Extreme care must also be taken when exposed to finely divided rare-earth metals and metallic powders to avoid pyrophoric burns from rapid and possibly instantaneous oxidation, especially if inhaled. Certain finely divided rare-earth metals, alloys, and powders, may also present the additional hazard of oxidizing rapidly enough to explode.

Employment.—Rare-earth mine and mill employment, based on the quarterly average number of workers, is shown in figure 10. Data were furnished by the U.S. Department of Labor and compiled by the Bureau of Mines.

Productivity Trends.—The 11-year trend for U.S. rare-earth mine productivity, based on capacity utilization, shows a slight increase for monazite and a slight decrease for bastnasite. However, gains were made during the period as improved mining plans and recovery methods were initiated at the rare-earth mines in California and Florida.

[1]Renison Goldfields Consolidated Limited. Annual Report, 1989, p. 12.

[2]Free on board/free into container depot.

[3]Metal Bulletin (London). Non-Ferrous Ores in Europe. Dec. 30, 1988, p. 36.

[4]Values have been converted from Australian dollars (A$) to U.S. dollars (US$) at the exchange rate of A$1.1710-US$1.00 based on yearend 1988 foreign exchange rates reported by the Wall Street Journal.

[5]Values have been converted from Australian dollars (A$) to U.S. dollars (US$) at the exchange rate of A$1.2660-US$1.00 based on yearend 1989 foreign exchange rates reported by the Wall Street Journal.

[6]Hedrick, James B. Availability of Rare Earths. Am. Cer. Soc. Bull., v. 67, No. 5, May 1987, pp. 858-861.

[7]Industrial Minerals (London). New J-V to Evaluate Yangibana Rare Earths. No. 261, June 1989, p. 8.

[8]———. Rare Earths Refining Development. No. 267, Dec. 1989, p. 8.

[9]———. Rhone Poulenc RE Interest. No. 267, Dec. 1989, p. 68.

[10]American Metal Market. Nissho-Iwai Buys RZM, Cable Units. Dec. 27, 1989, p. 2.

[11]Mining Annual Review. Pacific and Australasia. p. A71.

[12]Industrial Minerals. Australmin Minsands Production. No. 268, Jan. 1990, p. 8.

[13]Mining Magazine. Eneabba Sands Go-Ahead. Aug. 1989, p. 99.

[14]Industrial Minerals (London). Australia-Scott River Mineral Sands Interests. No. 265, Oct. 1989, p. 12.

[15]Mining Journal (London). North Broken Hill Rings New Changes. V. 313, No. 8044, Nov. 3, 1989, pp. 376-377.

[16]Work cited in footnote 11.

[17]Mining Magazine. The Sands of Cooljarloo. V. 160, No. 7, July 1989, pp. 6-7.

[18]Anuário Mineral Brasileiro 1988. Monazita (translated from Portuguese). pp. 264-265.

[19]———. Terras Raras (translated from Portuguese). pp. 320-321.

[20]Mining Magazine. Rare Earths from Brazil. V. 160, No. 7, July 1989, p. 19.

[21]Robjohns, Nicola. Rare Earths. Met. & Miner. Annu. Rev., p. C84.

[22]China Rare Earth Information. China Rare Earth 1989. No. 17, May 1990, pp. 1-2.

[23]Chori Co. Ltd., High-Tec Division. Scandium (translated from Japanese). China and Rare Metals. No. 94, May 1988, p. 29.

[24]Industrial Minerals (London). Danish Minsands Evaluated. No. 267, Dec. 1989, p. 9.

[25]Jones, Grayden. Hecla Seeking Rare Minerals in Greenland, (Article in the Spokane Spokesman newspaper), Aug. 9, 1989.

[26]Bondam, Jan. Greenland. Min. Annu. Rev., p. A184.

[27]Russell, A. Guyana's Industrial Minerals. Ind. Miner. No. 260, May 1989, pp. 61-67.

[28]Roskill's Letter from Japan. Demand for Scandium in Japan: 50% goes to Metal Halide Lamps. No. 154, Feb. 1989, p. 9.

[29]Ottley, Derek. Mineral Resources Potential of Malawi. Min. Mag. Feb. 1989, p. 129.

[30]Industrial Minerals (London). Fletcher Ilmenite Progress. No. 257, Feb. 1989, p. 13.

[31]Griffiths, Joyce. South Africa's Minerals: Diversity in Adversity. Ind. Miner. No. 263, Aug. 1989, p. 30.

[32]Mining Magazine. Namaqualand Sands. V. 161, No. 3, Sept. 1989, p. 179.

[33]Metal Bulletin (London). QIT Unit Puts Off South African Titanium Exploration. No. 7419, Sept. 25, 1989, p. 15.

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[35]———. Sale of the Century. No. 257, Feb. 1989, p. 14.

[36]Nakamura, Shigeo. Taiwan Rare Earths (translated from Japanese). China and Rare Metals. No. 94, May 1988, p. 87.

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[38]Work cited in footnote 8.

[39]Materials Edge. Magnesium Elektron-Opportunity Knocks for Yttrium-Based Castings. V. 1, No. 12, July-Aug. 1989, p. 12.

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[41]The Outlook-Annual Forecast. Standard & Poor's Corp. V. 61, No. 46, p. 2.

[42]Mariano, A. N. Economic Geology of Rare Earth Elements. Chap. 11 in Geochemisty and Mineralogy of Rare Earth Elements. Mineralogical Soc. of America, Review in Mineralogy, v. 21, pp. 309-337.

[43]Haley, T. J. Ch. 40 in Handbook on the Physics and Chemistry of Rare Earths, v. 4: Non-Metallic Compounds II. North-Holland Publ. Co., 1979, pp. 553-585.

TABLE 9

YEAREND RARE-EARTH CONCENTRATE PRICES

(Dollars per kilogram of rare-earth oxide contained)

Year	Bastnasite concentrate, 60% REO		Monazite concentrate, 55% REO plus thoria	
	Actual	Constant	Actual	Constant
1970	$0.66	$0.28	$0.37	$0.16
1971	.66	.29	.38	.17
1972	.66	.31	.35	.16
1973	.66	.33	.40	.20
1974	.79	.43	.42	.23
1975	.99	.58	.41	.24
1976	1.10	.69	.36	.23
1977	1.43	.96	.35	.24
1978	1.57	1.13	.58	.42
1979	1.87	1.47	.76	.60
1980	1.87	1.60	.81	.69
1981	2.03	1.91	.83	.78
1982	2.20	2.20	.75	.75
1983	2.03	2.11	.71	.73
1984	2.03	2.19	.64	.70
1985	2.03	2.25	1.09	1.12
1986	2.03	2.94	1.06	1.22
1987	2.20	2.58	.90	1.06
1988	2.31	2.80	1.15	1.39
1989	2.54	3.21	1.19	1.50

TABLE 10

TARIFF RATES

		Most favored nation (MFN)		Non-MFN	
		Jan. 1, 1989	Jan. 1, 1990	Jan. 1, 1989	Jan. 1, 1990
Thorium ores and concentrates (monazite)	2612.20.0000	Free	Free	Free	Free.
Rare-earth metals, intermixed or alloyed	2805.30.0000	$0.705/kg	$0.705/kg	$4.41 kg	$4.41 kg.
Cerium coumpounds[1]	2846.10.0000	7.2% ad val.	7.2% ad val.	35% ad val.	35% ad val.
Mixtures of rare-earth oxides or rare-earth chlorides	2846.90.2000	Free	Free	25% ad val.	25% ad val.
Rare-earth oxides except cerium oxide	2846.90.2010	Free	Free	25% ad val.	25% ad val.
Other rare-earth compounds or mixtures	2846.90.2050	Free	Free	25%	25%.
Other rare-earth oxides or other rare-earth chlorides[2]	2846.90.5000	3.7% ad val.	3.7% ad val.	25% ad val.	25% ad val.
Ferrocerium and other pyrophoric alloys	3606.90.3000	$.485/kg + 2.6% ad val.	$.485/kg + 2.6% ad val.	$4.41 kg + 25% ad val.	$4.41 kg + 25% ad val.

[1]Duty of 3.7% ad val. on certain yttrium, ore material, and compounds suspended through 1993.

[2]Duty on yttrium bearing material and compounds temporarily suspended in 1989 and 1990.

FIGURE 10

U.S. RARE-EARTH MINE AND MILL EMPLOYMENT

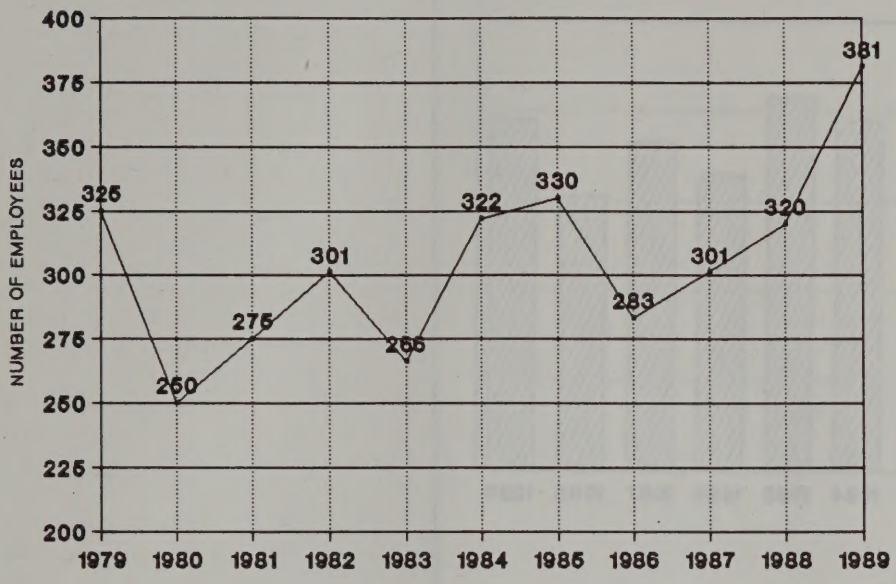


FIGURE 11

U.S. BASTNASITE CAPACITY UTILIZATION[1]

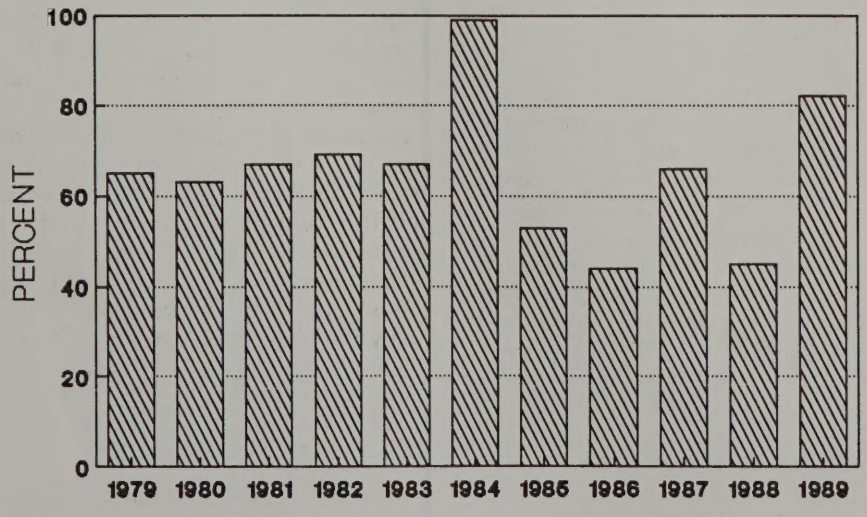
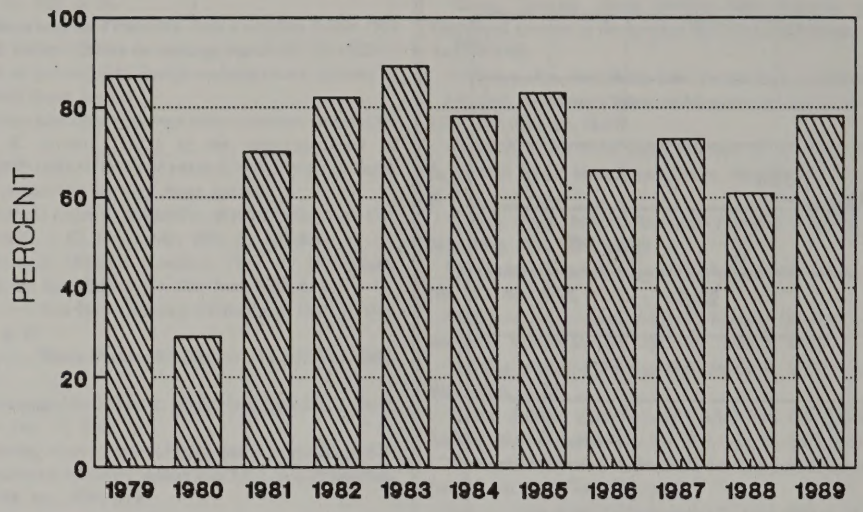
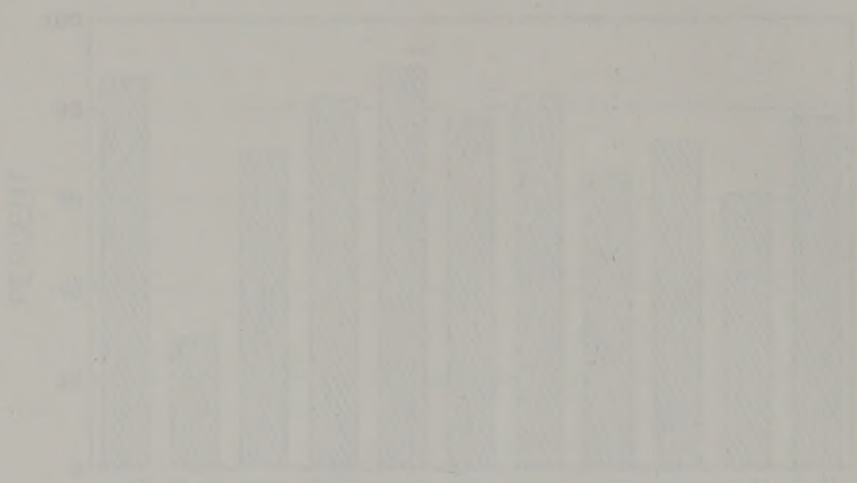


FIGURE 12

U.S. MONAZITE CAPACITY UTILIZATION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